Journal of Wind Engineering and Industrial Aerodynamics, 30 (1988) 233-241
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

EFFECT OF PARAMETRIC UNCERTAINTIES ON WIND EXCITED STRUCTURAL RESPONSE

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ABSTRACT

This paper addresses the influence of parametric uncertainties on the wind excited response of structures. Based on the available experimental data from both laboratory and field studies, the variability in the parameters related to the wind environment and meterological data, kinematics of wind flow field, wind-structure interaction and structural properties is assessed. The random variability in the parameter space is propagated to ascertain its influence on the structural response statistics utilizing a Monte Carlo simulation technique. By means of an example, the influence of parametric uncertainties on the dynamic response of a tall reinforced concrete chimney is presented. The analysis of simulated data suggests a need for further improvement in the modeling of wind-structure interaction, prediction of natural frequencies and damping, and a reduction in the variability of extreme wind estimates.

INTRODUCTION

The uncertainties associated with various parameters related to the dynamic effects of wind on structures introduce variability in the dynamic response estimates. These uncertainties in parameters arise from variability in the wind environment, meteorological data, wind-structure interaction and structural properties. The complexity of the dynamic wind load effects, compounded by a lack of understanding of the mechanisms that relate them to the far-field wind fluctuations, and scarcity of both full-scale and experimental data have introduced significant levels of variability in their quantification. Previous studies related to the reliability analysis of wind excited structures have examined the influence of varability of these parameters on the structural reliability (1, 2, 3, 4, 5, 6). In this study the influence of parametric uncertainties on the wind excited response of structures is examined.

In the following sections, the quantification of aerodynamic loads and the associated probabilistic response are discussed. Next, the influence of parameter uncertainty on the loading and structural response is analyzed. Finally, an example is presented to illustrate the influence of uncertainty on the dynamic response of a tall reinforced concrete chimney.

AERODYNAMIC LOADS

Notwithstanding the improved knowledge of wind effects on structures over the past few decades, our understanding of the mechanisms that relate the random wind field to the various wind induced effects on structures has not developed sufficiently for functional relationships to be formulated. Not only is the approach wind field very complex, but the flow pattern generated around

0167-6105/88/$03.50

a structure is complicated by the distortion of the wind field, the flow separation, the vortex formation, and the wake development. These effects cause large pressure fluctuations on the surface of a structure which in turn impose large overall aerodynamic loads upon the structural system and lead to intense localized fluctuating forces over the envelope of the structure. Under the collective influence of these fluctuating forces, a structure may vibrate in rectilinear and torsional modes. The alongwind, acrosswind and torsional load effects may be obtained by the synthesis of a random pressure field acting on the surface of a structure utilizing the covariance integration scheme (7). This scheme requires a description of the random pressure field in terms of the power spectral density of the point pressure fluctuations as well as the co-spectra between any two locations over the surface of the structure which are often nonhomogeneous. Alternatively, knowledge of the variance and frequency dependent spatial scales of a 2D-space and time pressure field in terms of the local averages may facilitate quantification of load effects on structures. As pointed out earlier, due to a lack of our understanding of the mechanisms that relate the random velocity field to the pressure field, no functional relationship exists; therefore, experimentally derived descriptions of the random pressure field have been introduced in lieu of the solution of equations of motion around structures (7,8,9). One exception of the alongwind direction exists in which, following the strip and quasi-steady theories, the fluctuating pressure field is assumed to be linearly related to the fluctuating velocity field (10,11). Force balance techniques and aeroelastic model tests may be utilized to directly determine the dynamic wind induced loads on structures (12,13). Both approaches have their advantages and some shortcomings (12). The structural motion may also induce additional loads that can be expressed in terms of the aerodynamic damping (14, 15, 16). In the case of aeroelastic model tests, motion induced loads are explicitly included in the measurements.

PROBABILISTIC DYNAMIC RESPONSE

The wind induced response of structures results from fluctuations in the far-field turbulence, and loads resulting from wind-structure interaction. The fluctuating response components may be evaluated either in time or frequency domain based on random vibration theory.

Besides the parametric uncertainties associated with aerodynamic loading, uncertainties related to the structural properties impart variability in the prediction of the overall structural response. Variability in the system parameters such as mass, stiffness and damping may arise either from spatially random variations in the material properties, its fabrication, or in its mathematical idealization. For example, the contribution of partition walls and some cladding components of high-rise buildings introduces variability in the overall system stiffness estimates. Once the spatial randomness in the structural properties becomes sizeable, the need to incorporate these uncertain characteristics in the dynamic analysis as random variables becomes significant. In the section on the propagation of uncertainties, methods to evaluate the influence of the foregoing variability in the structural parameters on the system response are discussed.

ANALYSIS OF UNCERTAINTY

Uncertainty in the desciption of the wind loads, compounded by the variability in the dynamic characteristics of a structural system is reflected in the dynamic response. These uncertainties are examined here systematically. The parameters are broadly classified into three categories: (a) wind environment and meteorological data, (b) parameters reflecting wind-structure interactions, and (c) structural properties.

Wind Environment and Meterological Data

In any design application the expected maximum response of a wind sensitive structure is computed based on the extreme wind speed over the lifetime of the structure. For serviceability requirements the lifetime of the structure may be expressed in terms of some alternative interval. The estimation of the lifetime extreme wind speed involves a selection of a model for predicting the maximum yearly wind using the best fitting cumulative distribution function of annual maximum mean hourly wind speed, which is further converted to a probabilistic description of the maximum lifetime wind speed. The estimation of design wind speeds has inherent modeling, sampling, and observation errors (4, 20). Additional uncertainty is introduced as a result of adjustment in the averaging period of wind from the fastest-mile wind speed to the mean hourly wind speed, the transformation of wind speed from one terrain to another, and wind directionality and its sensitivity to local site topography.

Parameters of Wind Flow Field

The power law exponent used to represent the height variation of wind speed, decay constants employed in the functional representation of spatial coherence of random wind field, and the surface drag coefficient used to represent the terrain roughness in the wind spectrum all add variability in the parameters involved in defining the wind flow field. There are several descriptions of the power spectra available in the literature over a variety of terrains (20, 21). In general, the spectral forms tend to agree in that they approach the Kolmogorov limit at high frequencies; all differ in their treatment of the low frequencies (21). For land based structures the variability introduced by the choice of spectral description is relatively small as compared to the compliant offshore platforms due to their low natural frequencies. The length scale of turbulence is another flow field parameter which exhibits variability and is sensitive to the method of estimation.

Wind-Structure Interaction

The drag and lift force coefficients, and Strouhal number are dependent upon the cross-section, aspect ratio, surface roughness, turbulence length scale and intensity, and shear in the approach flow. For structures of curvilinear cross-section, the dependence of drag and lift force coefficients and Strouhal number upon Reynolds number introduces additional variability in their estimated values. The acrosswind loading on structures is sensitive to the Strouhal number and the spectral bandwidth (4, 9, 15, 22). Any variability in these parameters is reflected in the description of the acrosswind load effects. The parameters in the covariance integration models that represent the description of the space-time variations of the wind loads are generally assumed to be deterministic. There is a considerable amount of variability in the values of these parameters which leads to uncertainty in the overall estimation of the wind loads. The directly measured loads obtained by employing force balance or aeroelastic tests include uncertainties stemming from modeling errors to measurement errors that introduce variability in the measured loads. Spectral estimates of wind loads obtained from wind tunnel measurements at different laboratories exhibit significant variability (17).

Structural Properties

Despite the variability in the structural properties the previous studies have assumed that structural systems have deterministic mechanical characteristics or have implied that the variations in these properties were considerably smaller than those associated with the loading. The uncertainty introduced in the dynamic response of systems with statistical uncertainties in their mass or stiffness has received considerable attention recently and the problem is being investigated systematically utilizing perturbation, second-moment, stochastic finite element and Monte Carlo simulation techniques (23, 24, 25, 26, 27, 28).

In this study a simplistic treatment of the uncertainty in the stiffness and mass matrices was utilized. It was assumed that the mass and stiffness of two adjacent levels were perfectly correlated with equal coefficients of variation. Ideally, one may invoke a statistical dependence between the various levels in the random medium that decreases with their physical separation. Notwithstanding the attractiveness of such a representation from a qualitative point of view, it may become quantitatively arbitrary in the absence of information pertaining to the physical make-up of the medium being modeled. The stiffness and mass matrices were expressed as

$$[K] = K^{*}\,[\bar{K}]; \quad [M] = M^{*}\,[\bar{M}] \tag{1}$$

in which $[\bar{K}]$ and $[\bar{M}]$ are deterministic matrices consisting of the mean values of the stiffness and mass matrices respectively; K^* and M^* are random variables with mean values equal to unity and coefficients of variation equal to the COV of the elements of the stiffness and mass matrices, respectively. This representation has also been used by Portillo and Ang (29) and Rojiani and Wen (5). The natural frequencies of the system were expressed as

$$f_i = f^{*}\,\bar{f}_i \tag{2}$$

in which f^* is the random variable with mean value equal to unity, its coefficient of variation Ω_{f^*} is expressed in terms of Ω_{K^*} and Ω_{M^*} and $\bar{f}_i$ is the mean value of the ith natural frequency. The mode shapes become deterministic with the preceding assumption. A prediction error is included to account for the effect of this assumption.

The selection of an appropriate damping value is the subject of discussion and controversy. Although it is a general consensus that damping values change with amplitude, a general functional description is presently not available. Information available from full-scale measurements for analyzing the variability of damping has been assembled by Haviland (30). It provides estimates of the mean and coefficients of variation of damping values of steel and concrete buildings at low and high levels of response amplitudes. Information regarding damping in concrete chimneys is available among others in references 22 and 31.

TABLE I. Uncertainties of Various Basic Variables

Variable		Mean	COV	Distribution
Wind Speed		52.91	0.101	Extreme Value Type I
Drag Coefficient		0.7	0.14	lognormal
RMS Lift Coefficient		0.15	0.27	lognormal
Strouhal Number		0.20	0.11	lognormal
Spectral Bandwidth		0.25	0.30	lognormal
Aerodynamic Damping		--	0.30	lognormal
Natural frequency		--	0.17	lognormal
Structural Damping		--	0.35	lognormal
Element of mass matrix*		1.0	0.094	normal
Flexural Rigidity		--	0.18	normal
Element of stiffness matrix*		1.0	0.27	normal
Diameter		--	0.04	normal
Thickness		--	0.04	normal
Specific Weight of Concrete		150 lb/ft^3	0.03	normal
f'_c compressive stress in concrete				
	4000 psi	3390 psi	0.18	normal
	5000 psi	4028 psi	0.15	normal
E_c	4000 psi	3320 ksi	0.09	normal
	5000 psi	5000 psi	0.075	normal
E_s		29200 ksi	0.033	normal

PROPAGATION OF UNCERTAINTY

The dynamic response of a wind excited structure is a function of a number of uncertain variables whose uncertainty has been identified in the previous sections. The effects of uncertainty in these parameters is propagated in accordance with the functional relationship to assess the uncertainty in the system dynamic response. The propagation of uncertainty may be determined by employing one or more of the following approaches: a perturbation technique; a probabilistic finite element approach; a Monte Carlo simulation method; and a second-moment approach (23,24,25,26,27,28). In reference 4, the First-Order Second-Moment approximation was utilized to ascertain uncertainty in the dynamnic response of a tall reinforced concrete chimney in terms of the coefficients of variation. A Monte Carlo simulation approach was employed in this study to assess the performance of the First-Order Second-Moment approximation for this complex problem. The following example is presented to illustrate the simulation procedure.

EXAMPLE

A 598 ft. tall reinforced concrete chimney was utilized to evaluate uncertainty in the response estimates. The details of structural dimensions and other related information are given in reference 4. The chimney was discretized into 13 elements along the height, with a translational and a rotational degree-of-freedom at each node. The mass matrix was formulated using a consistent mass description. The mean value of the natural frequencies in the first three modes were computed to be 0.48, 1.86 and 4.71 Hz. The mean value of the structural damping was assumed to vary from 1% of the critical to 4% with an increment of 1%. The damping values in the higher modes were obtained following reference 4. A random vibration-based modal superposition technique was utilized to simulate the statistics of the chimney response components. Only the first three modes were included in the dynamic analysis.

The uncertainty in the design wind speed that corresponds to the lifetime extreme wind speed was evaluated from data pertaining to an arbitrarily selected industrial site. The extreme value Type I, Type II, and Rayleigh distributions were used to model the annual maximum wind speed distribution. The data provided the best fit to the Type I extreme value distribution based upon a maximum probability plot correlation coefficient (MPPCC) criterion (4,20). The estimates of the mean value and the COV for various flow related parameters were made from the experimental and field study data (4). The uncertainty in the stiffness matrix was estimated on the basis of uncertainty in the flexural rigidity, EI, of the tubular reinforced concrete section (4). Utilizing the COVs of the stiffness and mass matrices and including an additional uncertainty of 0.1 to include the influence of possible soil-structure interaction, the COV of the natural frequency was computed to be 0.17. Based on the analysis of structural damping data related to the reinforced concrete chimneys the COV was found to be 0.35. Due to a lack of data the same coefficient of variation was assumed for the damping in the higher modes.

Initially, a total of twenty-five basic variables associated with parameters reflecting the wind environment and meterological data, wind-structure interaction and structural properties were considered. A sensitivity analysis of the contribution of the uncertainty of various variables to the overall uncertainty suggested that the number of variables could be reduced to those which significantly influence the overall uncertainty in the response. A summary of the mean values of the parameters and their COVS are given in Table I.

The peak values of the alongwind and acrosswind chimney displacements at the top and associated base bending moments were simulated utilizing a Monte Carlo Simulation technique (4). The computer generated response estimates were statistically analyzed to provide the means and COVs. The complexity associated with the evaluation of the aerodynamic loads which include a double integration for each sample value, the subsequent estimation of the response including the first three modes in each orthogonal direction involved significant computational effort. On an AS9000 computer, six hours of CPU time were required to generate 14,000 samples of data. The results were not influenced by the sample size, once the number of simulated values reached 10,000. The sampling error introduced by limited sample size may be improved without increasing the sample size by utilizing variance reduction techniques, e.g., importance sampling, antithetic variates, conditional expectations and stratified sampling (2, 32, 34).

The response statistics are presented in Tables II and III. The results obtained by the simulation approach show good agreement with the FOSM approach (4). The estimates of uncertainty in the response may be utilized further to establish a limit state design procedure or reliability analysis of structures to ensure their safety and serviceability under wind loads.

TABLE II. Maximum Deflection at Top

Mean Value of Damping in the First Mode (%)	Alongwind Response		Acrosswind Repsonse	
	Mean(ft)	COV	Mean(ft)	COV
1	0.4029	0.773	0.8142	1.080
2	0.2889	0.695	0.4684	0.813
3	0.2371	0.696	0.3632	0.768
4	0.2076	0.727	0.3065	0.776

TABLE III. Maximum Base Bending Moment

Mean Value of Damping in the first Mode (%)	Alongwind Moment		Acrosswind Moment	
	Mean Value (lb-ft)	COV	Mean Value (lb-ft)	COV
1	0.1011906×10^9	0.774	0.2051884×10^9	1.073
2	0.7255618×10^8	0.695	0.1182936×10^9	0.804
3	0.5977762×10^8	0.716	0.9188896×10^8	0.761
4	0.5215667×10^8	0.728	0.7761918×10^8	0.773

CONCLUDING REMARKS

The uncertainties associated with aerodynamic loads and dynamic characteristics of wind excited structures have been identified and discussed. Based on the available experimental data from laboratory and field study measurements, the variability of the various parameters categorized as wind environment and meteorological data, wind-structure interaction and structural properties has been assessed. A Monte Carlo simulation technique has been utilized to generate samples of response estimates of a tall reinforced concrete chimney with uncertainty in the load effects and structural properties. The simulated data were used to estimate the mean and COVs of the response in terms of top deflections and corresponding base bending moments. The COVs for both components of response suggest a need for further improvement in the modeling of wind-structure interaction, prediction of natural frequencies and damping, and a reduction in the variability of extreme wind estimates.

ACKNOWLEDGEMENTS

The financial assistance for the research was provided in part by the National Science Foundation Grants CEE-8019392 and ECE-8352223. Their support is gratefully acknowledged. The author is grateful to J. Hsieh and W-J Sun for their assistance in developing the simulation program.

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